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Algorithm for the synthesis of a predictive control system for the tape pulling process

Isamidin Sidikov[1,*], *Davronbek* Khalmatov[1] and *Gulchekhra* Alimova[1]

[1]Tashkent Institute of Textile and Light Industry, 5, Shokhjakhon street, Tashkent, 100100, Uzbekistan

Abstract. Automation of the technological process of product manufacture via the application of contemporary management techniques is one approach to boost the production efficiency of the textile industry. Many characteristics of the manufacturing technology equipment should be considered in these techniques. This paper aims to present an algorithm for the synthesis of an automatic control system for the process of pulling the tape, based on the application of the predictive control method. To improve the quality of control by reducing the static error and over-regulating the transient process, an integral component was introduced into the control system circuit, which allows us to give the properties of the astatism of the system, taking into account the implementation of restrictions imposed on state variables and setting influences. Based on the comparative analysis, the advantages of the proposed approach are determined, which allows ensuring good performance of the control system in conditions of various types of disturbances. The proposed algorithm is versatile and can be applied to a control system, provided that strict restrictions are imposed on the control object on the disturbing effects and on the dynamic properties of the object.

1 Introduction

One of the ways to increase the production efficiency of the textile industry is the automation of the technological process of manufacturing products, through the use of modern management methods. These methods should take into account a number of features of the technological equipment used in production. These conditions associated with the rigid stabilization of technological parameters during the formation and winding of the fibrous material impose high requirements on automatic control systems in relation to [1, 2] maintaining the specified speed modes and quality indicators of the fibrous material.

Currently, the process of pulling fibrous materials and the influence of working bodies on them is directly carried out by means of controlled by an adjustable electric drive. Modern methods and technologies have not been properly used for the development and research of complex controlled electrical complexes [3, 4]. It should be noted that the development of effective methods for managing complex dynamic objects of technological equipment is a promising task. The use of modern methods and technologies for managing complex dynamic objects requires the development of a methodology based on the use of

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* Corresponding author: i.sidikov@titli.uz

specific technologies, taking into account the peculiarities of the physical process taking place on the considered one, it should be noted that the development of effective methods for managing complex dynamic objects of technological equipment is a promising task [5].

The use of modern methods and technologies for managing complex dynamic objects requires the development of a methodology based on the use of specific technologies, taking into account the peculiarities of the physical process taking place on the object under consideration [6]. In this regard, there are problems of creating highly efficient control systems that take into account the appearance of various types of vibrations due to the elasticity of both electro-mechanical mechanisms (transients in an electric motor, elasticity of flexible gears, rigidity of mechanical gears, moments of inertia and resistance) and metrological factors (measurement noise in feedback channels, accuracy of coefficients of mathematical models) [7].

These and other complexity factors significantly affect the energy and resource costs of production, due to the wear of the mechanisms of technological units, increased downtime of equipment and deterioration of product quality. It should be noted that the development of effective methods for managing complex dynamic objects of technological equipment is a promising task [8]. The use of modern methods and technologies for managing complex dynamic objects requires the development of a methodology based on the use of specific technologies, taking into account the peculiarities of the physical process taking place on the considered one, it should be noted that the development of effective methods for managing complex dynamic objects of technological equipment is a promising task [9]. The use of modern methods and technologies for managing complex dynamic objects requires the development of a methodology based on the use of specific technologies, taking into account the peculiarities of the physical process taking place on the object under consideration [10].

In this regard, there are problems of creating highly efficient control systems that take into account the appearance of various types of vibrations due to the elasticity of both electro-mechanical mechanisms (transients in an electric motor, elasticity of flexible gears, rigidity of mechanical gears, moments of inertia and resistance) and metrological factors (measurement noise in feedback channels, accuracy of coefficients of mathematical models) [11, 12]. These and other complexity factors significantly affect the energy and resource costs of production, due to the wear of the mechanisms of technological units, an increase in the downtime of equipment and a deterioration in product quality.

One of the ways to ensure energy saving is to create a system of optimal predictive control of technological objects according to the criterion of minimizing energy consumption in the conditions of real functioning of the system, i.e. when the properties of dynamic objects, its operating modes, restrictions imposed on state variables associated with the condition of the operating modes of the units change [13]. Under these conditions, the saving of electricity consumed by the units is ensured by optimal control of the technological parameters of the process (for example, the linear density of the tape) [14].

It should be noted that the process of pulling the fibrous material is directly related to the speed modes of technological units, which allow for synchronization of the movements of the working bodies of the equipment [15]. To reduce the energy consumption consumed by technological equipment, it is necessary to ensure the choice of rational speed modes of electromechanical systems, which are determined by energy indicators and requirements for technological processes [16]. The considered tape pulling is one of the most complex technological processes, due to the variety of fiber composition and also due to the strong influence on the accuracy of the control of the fiber product tension process [17]. An important task in the development of a control system for the process of pulling the tape is to ensure the coordinated movement of the working bodies of the technological equipment. One of the ways to solve the problem under consideration is to create a control of the process of pulling the tape with a predictive model using the methods of modern management theory and information technology.

Based on the modern nonlinear control theory, the paper presents an algorithm for the synthesis of a predictive control system for a spinning machine and a winding device. The effectiveness of these algorithms is that they allow you to adapt the control systems to the changing parameters of the object and external influences.

2 Materials and methods

Choosing the laws of regulation and determining the optimal tuning parameters of the controller when solving the problem of synthesizing an automatic control system for the process of pulling a tape that functions under strict restrictions imposed on state variables and controls is a difficult task to solve. In this regard, in order to solve this problem, a highly efficient algorithm for the synthesis of the control system of the process under consideration is proposed, based on the application of the predictive control method, which is close to the optimal control method with a predictive model based on a generalized criterion [8].

The essence of the proposed algorithm is that for predicting the behavior of a control system with a predictive model, an integral component is additionally introduced into the control loop, which ensures high control accuracy.

The dynamics of the considered digital control system for the tape pulling process is described by the equation state space:

$$x(k+1) = A(x) + Bu(k) + Dw(k), \quad y(k) = Cx(k) \tag{1}$$

where $x(k)$ - state vector, $u(k)$ - control vector, $y(k)$ - output vector, $w(k)$ - perturbation vector. $ABCD$ - matrices of appropriate sizes. The range of changes in the state and control variables is set by inequalities, taking into account the permissible value of the change in parameters corresponding to the technological regulations

$$x_{min} \leq x(k) \leq x_{max} \qquad u_{min} \leq u(k) \leq u_{max}$$

It is necessary to determine the control law that ensures the fulfillment of the condition $lim y(k) = v \; by \; k \to \infty,$ where v - desired output value.

In this case, the solution of the problem of optimizing the quadratic quality functional for each moment of time using the predictive control method is formulated as follows:

$$J = \sum_{i=1}^{p}\left(\|v - y(k+i/k)\|_Q^2 + \|u(k+i-1/k)\|_R^2\right) \tag{2}$$

under restrictions:

$$x_{min} \leq x(k+i/k) \leq x_{max}\,, \quad u_{min} \leq u(k+i/k) \leq u_{max} \quad i = 1,2,3, \dots p,$$

where p - The final value is the number of controls, Q - symmetric non-negative matrix, R - symmetric positive definite weight matrix.

Denoting $\varepsilon(k) = v - y(k)$, we get the vector $z(k)$, defined by the equation

$$z(k+1) = z(k) + \varepsilon(k).$$

Here is the vector $z(k)$ it is an integral of the tracking error. Then predicting the behavior of the control system at various points in time, taking into account the vector $z(k)$, it consists of the following sequence.

Replacing the quality functional (2) with a functional containing an integral component, we obtain the quality criteria in the following form:

$$J = \sum_{i=1}^{p} \left(\|v - y(k+i/k)\|_Q^2 + \|z(k+i+1/k)\|_N^2 + \|u(k+i-1/k)\|_R^2 \right), \quad (3)$$

where N - symmetric positive-definite matrix.

To reveal the essence of the method, we introduce the following notation:

$$\bar{x}(k) = \begin{bmatrix} x(k+1/k) \\ x(k+2/k) \\ \vdots \\ x(k+p/k) \end{bmatrix}, \qquad \bar{u}(k) = \begin{bmatrix} u(k/k) \\ u(k+1/k) \\ \vdots \\ u(k+p-1/k) \end{bmatrix},$$

$$\bar{w}(k) = \begin{bmatrix} w(k/k) \\ w(k+1/k) \\ \vdots \\ w(k+p-1/k) \end{bmatrix}, \qquad \bar{z}(k) = \begin{bmatrix} z(k+2/k) \\ z(k+3/k) \\ \vdots \\ z(k+p+1/k) \end{bmatrix},$$

$$F_x = \begin{bmatrix} A \\ A^2 \\ \vdots \\ A^p \end{bmatrix}, \quad F_y = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^p \end{bmatrix}, \quad F_z = \begin{bmatrix} C(E_n + A) \\ C(E_n + A + A^2) \\ \vdots \\ C(E_n + A + \cdots + A^2) \end{bmatrix},$$

$$G_x = \begin{bmatrix} B & 0 & \dots & 0 \\ AB & B & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{p-1}B & A^{p-2}B & \dots & B \end{bmatrix}, \qquad G_y = \begin{bmatrix} CB & 0 & \dots & 0 \\ CAB & CB & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{p-1}B & CA^{p-2}B & \dots & CB \end{bmatrix},$$

$$G_z = \begin{bmatrix} CB & 0 & \dots & 0 \\ C(E_n + A)B & CB & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ C(E_n + A + \cdots + A^{p-1})B & C(E_n + A + \cdots + A^{p-2})B & \dots & CB \end{bmatrix},$$

$$S_x = \begin{bmatrix} D & 0 & \dots & 0 \\ AD & D & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{p-1}D & A^{p-2}D & \dots & D \end{bmatrix}, \quad S_y = \begin{bmatrix} CD & 0 & \dots & 0 \\ CAD & CD & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{p-1}D & CA^{p-2}D & \dots & CD \end{bmatrix},$$

$$S_z = \begin{bmatrix} CD & 0 & \dots & 0 \\ C(E_n + A)D & CD & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ C(E_n + A + \cdots + A^{p-1})D & C(E_n + A + \cdots + A^{p-2})D & \dots & CD \end{bmatrix},$$

Taking into account these notations in accordance with (1), we obtain:

$$\begin{gathered} \bar{x}(k) = F_x x(k) + G_x \bar{u}(k) + S_x \bar{w}(k), \\ y(k) = F_y x(k) + G_y \bar{u}(k) + S_y \bar{w}(k), \\ \bar{z}(k) = L_y z(k) + L_z v - F_z x(k) - G_z \bar{u}(k) - S_z \bar{w}(k). \end{gathered}$$

$$L_x = \begin{bmatrix} E_n \\ \vdots \\ E_n \\ E_n \end{bmatrix}, \quad L_y = \begin{bmatrix} E_l \\ \vdots \\ E_l \\ E_l \end{bmatrix}, \quad L_u = \begin{bmatrix} E_m \\ \vdots \\ E_m \\ E_m \end{bmatrix}, \quad L_z = \begin{bmatrix} 2E_l \\ \vdots \\ pE_l \\ (p-1)E_l \end{bmatrix}$$

where E_n, E_l, E_m - unit size matrices n, l and m accordingly.

Then the quality functional (3) has the following form

$$J = \left\| L_y v - F_y x(k) - G_y \bar{u}(k) - S_y \bar{w}(k) \right\|_{\bar{Q}}^2 + \\ + \left\| L_y z(k) + L_z v - F_z x(k) - G_z \bar{u}(k) - S_z \bar{w}(k) \right\|_{\bar{N}}^2 + \| \bar{u}(k) \|_{\bar{R}}^2 \quad (4)$$

where $\bar{Q}$, $\bar{N}$ and $\bar{R}$ - block diagonal matrices whose diagonal elements consist of matrices Q, N and R. Then the constraints on the state and control variables are written as

$$L_x x_{min} \leq F_x x(k) + G_x \bar{u}(k) + S_x \bar{w}(k) \leq L_x x_{max}. \quad (5)$$

$$L_u u_{min} \leq \bar{u}(k) \leq L_u u_{max}. \quad (6)$$

This problem is a quadratic programming problem with respect to a vector of unknowns $\bar{u}(k)$ with the objective function (4) constraints (5), (6).

The solution of the problem (4)-(6) is performed iteratively, that is, it is solved at each moment of time. At the same time, the values of the control actions at the moment of time k is taken equal to $u(k/k)$ [10, 11].

3 Results and discussion

Let there be an exhaust device equipped with a DC electric motor. It is required to synthesize control systems for the angular velocity of rotation of the shaft of a DC electric motor. Certain restrictions are imposed on the values of the regulated variables (angular velocity and current strength). The dynamics of the electric motor is described by the equations:

$$J\dot{\omega} = k_1 I + M, \quad (7)$$

$$L\dot{I} + RI = -k_2 \omega + u, \quad (8)$$

where ω - angular velocity; I - current strength; u - voltage ; M - moment of action of external forces; J - moment of inertia of the motor shaft; L - the inductance of the anchor circuit; R - resistance of the anchor chain; k_1, k_2- design parameters of the engine.

The discrete model of the control system under consideration has the following form:

$$X(h+1) = \bar{A}(h) \cdot X(h) + \bar{B} \cdot U(h)$$

$$Y(h) = \bar{D} \cdot X(h)$$

Here, $\bar{A}$, $\bar{B}$, $\bar{D}$ - the matrix of a continuous system, represented as:

$$\bar{A} = \begin{bmatrix} 0 & \frac{k_1}{J} \\ -\frac{k_2}{L} & -\frac{R}{L} \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}, \quad \bar{D} = \begin{bmatrix} \frac{1}{J} \\ 0 \end{bmatrix}$$

Here the constraints on state and control variables are represented by inequalities.

$$|\omega(t)| \le 100\, rad/s, \quad |I(t)| \le 5\, A, \quad |U(t)| \le 10\, V.$$

In this case, the control actions are generated by a microcontroller and formed by an amplitude-pulse modulator with a quantization step in time h.

To simulate the dynamics of the considered control system for the tape drawing process, the MATLAB software package was used for the following values of the parameters of the control object:

$J = 0.68\, kg \cdot m^2$; $L = 0.0052\, Hz$; $K = 0.45\, \Omega$; $k_1 = 7.14$; $k_2 = 0.098$ and the control algorithm: $h = 0.1$; $p = 5$; $Q = 1$; $N = 1$; $R = 1000$.

Figure 1 shows the transients (angular velocity, current strength and control) flowing into the systems for $v = 20, 50, 80$ and $M = 5$. The simulation results showed that the developed algorithm for the synthesis of a control system with a predictive model provides high control accuracy by giving the system the properties of astatism, unlike standard algorithms.

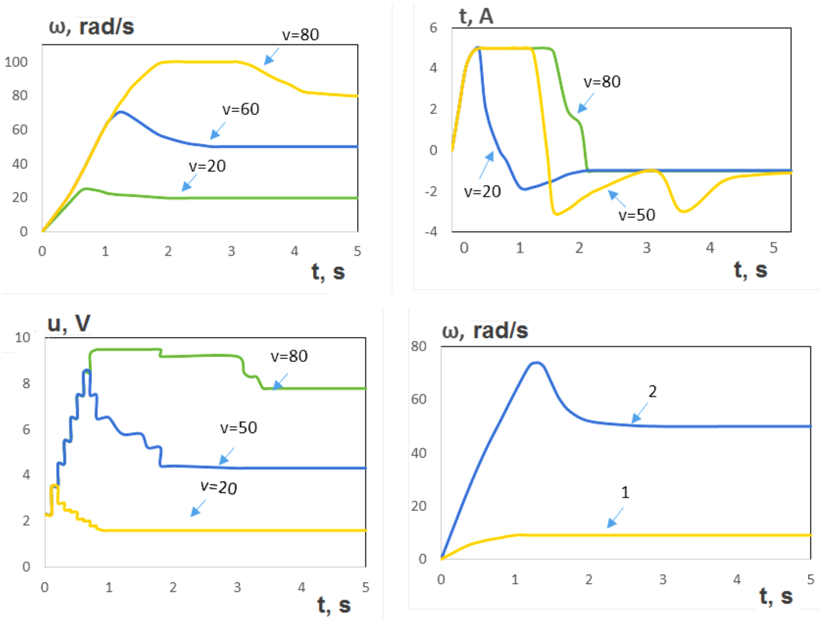

Fig. 1. Graphs of transients.

4 Conclusions

An algorithm for the synthesis of a control system for the process of pulling fibrous materials based on the method of predictive control, including an integral component, is proposed. The inclusion of an integral component in the control circuit of the system allows you to reduce the static error of control and over-regulation of the transient process, which ensures high control quality. The results of modeling and comparative analysis with the standard predictive control algorithm confirmed the theoretical conclusions and showed good performance of control systems in real-life objects**.**

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